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Refractivity in the Arctic regions

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NAVAL POSTGRADUATE SCHOOL

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THESIS

REFRACTIVITY IN THE ARCTIC REGIONS

by

Keir D. Stahlhut

September 2006

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The purpose of this study is to quantify patterns or trends of electromagnetic ducting conditions in the Arctic. On average, ducts occurred 5% of the time in the summer months, and 2-3% in the spring, fall, and winter months. This is considered a low approximation due to the vertical resolution of the sounding data. For some local regions, ducts occurred up to 20% of the time, especially in summer months. In general, local areas near coast lines or near the pole over ice/ocean had higher frequency of ducts than local areas over land mass. For summer and fall months, humidity gradients contributed most to the formation of a duct, while temperature gradients contributed to a lesser degree. For spring months, temperature gradients contributed most to the formation of the duct, while humidity gradients contributed to a lesser degree. For winter months, due to the extremely cold surface temperatures and low available humidity, temperature gradients were the dominant contribution to duct formation, and humidity gradients worked against duct formation.

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REFRACTIVITY IN THE ARCTIC REGIONS

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ABSTRACT

The purpose of this study is to quantify patterns or trends of electromagnetic ducting conditions in the Arctic. On average, ducts occurred 5% of the time in the summer months, and 2-3% in the spring, fall, and winter months. This is considered a low approximation due to the vertical resolution of the sounding data. For some local regions, ducts occurred up to 20% of the time, especially in summer months. In general, local areas near coast lines or near the pole over ice/ocean had higher frequency of ducts than local areas over land mass. For summer and fall months, humidity gradients contributed most to the formation of a duct, while temperature gradients contributed to a lesser degree. For spring months, temperature gradients contributed most to the formation of the duct, while humidity gradients contributed to a lesser degree. For winter months, due to the extremely cold surface temperatures and low available humidity, temperature gradients were the dominant contribution to duct formation, and humidity gradients worked against duct formation.

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I. REFRACTIVITY CONDITIONS IN THE ARCTIC

A. INTRODUCTION

The vertical gradient of the modified index of refraction (M), affects the propagation of electro-magnetic (EM) energy in the UHF, VHF, and microwave frequency bands in the troposphere. The modified index of refraction is a function of atmospheric pressure (p), temperature (T), the partial pressure of water vapor (e), and height above ground (z). When atmospheric conditions exist to cause the vertical gradient of M to be negative, EM energy will be trapped in a vertical duct allowing for increased horizontal propagation distances. The purpose of this study is to quantify patterns or trends of ducting conditions in the Arctic. These results represent the first climatology of refractive conditions ever published for the Arctic region and could be useful for planning operations involving EM energy in the Arctic.

B. BACKGROUND

1. Modified Refractivity

The phase speed of EM waves passing through the atmosphere is affected by the index of refraction (n). To avoid using values that are nominally close to 1, a conversion is made to refractivity (N), by subtracting one from n and multiplying by 10^6. The vertical gradient of N determines how EM energy will propagate through the atmosphere in relation to the horizontal. When dN/dz is positive, energy is bent upward from horizontal propagation, and ranges of EM energy will be decreased and classified as "sub-refractive." When dN/dz is between 0 and -79 km^{-1}, horizontal propagation ranges will be "normal." When dN/dz is between -79 and -157 km^{-1}, ranges will be increased and classified as "super-refractive." When dN/dz is less than -159 km^{-1}, propagation ranges will be greatly increased and considered "trapped" within a vertical duct. To normalize these values for better visual inspection, Modified Refractivity (M) is used where $M = N + 0.157z$, where z is the height above the surface in meters. The second term accounts for the Earth's curvature. Ducts will then occur at heights where dM/dz is negative (Davidson, 2002).

2. Arctic Region Data Sets

The data sets used for this study were taken from four different sources. The first was obtained from the National Snow and Ice Data Center (NSIDC), titled the Historic Arctic Rawinsonde Archive (HARA). The data set contains approximately 1.5 million vertical atmospheric soundings pole ward of 65 degrees north, taken from 1948-1996 (Kahl et. al, 1992 and Serrezze and Shiotani, 1997). The second data set was also obtained from NSIDC, titled the Daily Arctic Ocean Rawinsonde (DAOR) Data from Soviet Drifting Ice stations. This data set contained roughly 25,000 soundings taken from former Soviet drifting platforms, from 1954 to 1990, pole ward of 70 degrees north latitude (Kahl, 1998; Kahl et. al, 1999). The third data set, titled The Ptarmigan Dropsonde Archive, consists of 10,000 soundings take from 1950-1961 as part of a U.S. Air Force weather reconnaissance program (Kahl et. al, 1992). The fourth data set was obtained from the Forecast Systems Laboratory (FSL)/ National Climatic Data Center (NCDC) Radiosonde Data Archive. Almost 200,000 soundings were available from this source, taken from 1998-2006.

For a particular sounding, temperature, pressure, dew point depression, and height above the surface were recorded for generally 20 to 40 vertical levels. By processing this data through various MATLAB routines, a vertical profile of M, along with dM/dz for each individual sounding in time and space were calculated and the cumulative results used for analysis.

A large number of the soundings had missing data fields, especially above the surface. Soundings from earlier in the time period rarely had a vertical resolution of better than 50 mb. More recent soundings had better vertical resolution, but had many unrecorded values throughout the sounding.

C. IMPORTANCE TO NAVAL APPLICATIONS

The end goal of this study is to develop a regional and descriptive analysis of the climatological aspects of refractivity in the arctic regions, and thus provide perspective on devices using EM energy might perform in one geographical region relative to another. That is, to locate geographic regions of higher or lower relative frequency of occurrence of ducting conditions in the atmosphere. By comparing climatological statistics on parameters directly affecting the useful range of, for example, a ship's

surface search radar, one might be able to prepare charts or displays for use in military operational planning in order to quantify and/or bound the predicted performance of a ship's sensors for a given geographic region. Such data could be used to help decide on the best available location for a particular EM system performance, or to provide a prediction of system performance for a given geographic location. Due to global warming, the Arctic is likely to become increasingly important for shipping as the Arctic ice extent recedes. In this possible future scenario, knowledge of how communications and radar systems performance are affected in these areas may be increasingly important and are identified as an operational shortfall for future operations of U.S. Naval assets in these regions (Office of Naval Research et. al, 2001).

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II. METHODOLOGY

A. THEORY AND FORMULAS USED

1. Types of Ducts

There are three types of ducts (Figure 1). The upper piece of the duct, caused by a negative gradient of M, is called the trapping layer. It extends from the height of the local minimum of M to the height of the local maximum of M. The subsequent lower piece of the duct extends from the portion from the height of the local maximum of M to the height where M is the same value as that of the duct top, or to that of the surface.

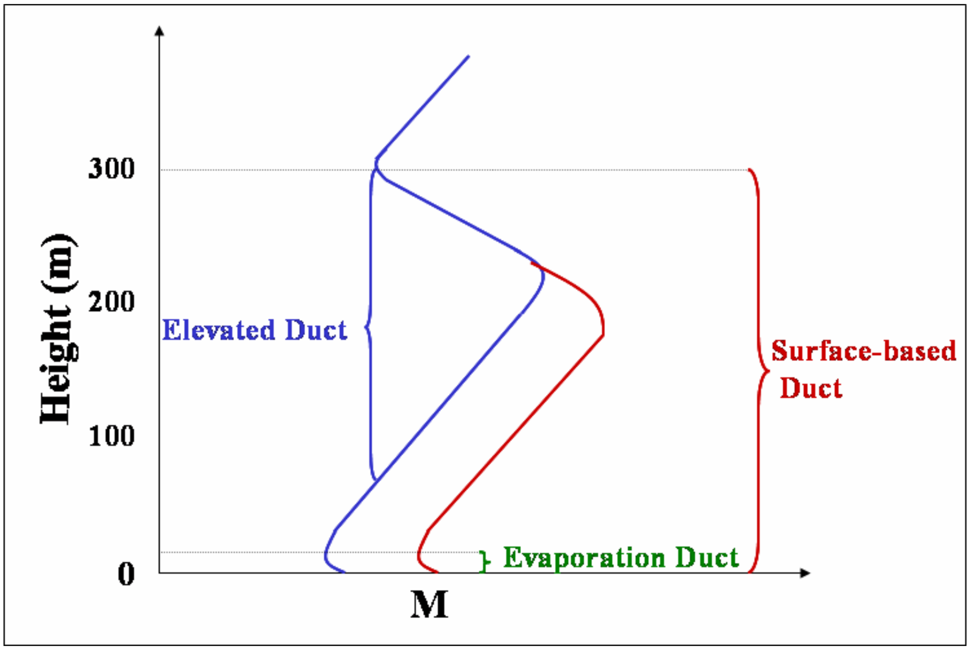

Figure 1. Examples of the three types of ducts (Davidson, 2002).

a. Evaporative Duct

Near the surface, over a liquid ocean, a strong humidity gradient exists which causes a very shallow near-surface duct called an evaporative duct. Rawinsondes and dropsondes do not have sufficient vertical resolutions to resolve such a shallow depth feature (typically less than 20 meters); therefore this type of duct is not examined in this study.

b. Surface-based Duct

In this situation, the value of M at the duct top (the local minimum) is less than the value of M at the surface. Typically, this minimum occurs at the top of the inversion which caps the atmospheric boundary layer where the relatively warm and dry air in the free atmosphere exists above the cool and moist boundary layer air. This can be caused by several processes (often in combination) including large scale subsidence, boundary layer mixing, or advection of warm, dry air over a cool surface.

c. Elevated Duct

This type of duct is similar to the surface-based; however the value of M at duct top (the local minimum) is greater than at the surface, which means that the duct bottom is above the surface. This situation is generally caused by temperature and/or humidity inversions likely associated with subsidence in high pressure systems or frontal boundaries.

2. Formulas

To calculate an M profile and subsequent duct description information based on each individual sounding, the following formulas were used. To calculate M at a given height (in meters) from the sounding,

$$M(z) = 77.6\frac{p(z)}{T(z)} - 5.6\frac{e(z)}{T(z)} + 375000\frac{e(z)}{[T(z)]^2} + 0.157z \,, \qquad (1)$$

where p (mb) is atmospheric pressure at a given height, e (mb) is vapor pressure of air at a given height, T (K) is air temperature at a given height, and z (m) is the height above the surface (Davidson, 2002). The vapor pressure for a given dew point temperature, T_d (C),

$$e(T_d) = 6.1121e^{\left(\frac{22.587T_d}{273.86+T_d}\right)} \,, \qquad (2)$$

is obtained from a derivation of the Magnus formulas, named AEKRi (Alduchov and Eskridge, 1996). The duct top and optimal coupling height (or duct middle) is simply a local minimum or local maximum of M, respectively, found by a switch in the sign of dM/dz. The duct bottom, z^*, is the height at which the same value of M is found at the

duct top, which can be visualized by dropping a straight vertical line from the duct top to the duct bottom. By applying simple geometry,

$$z^* = z_2 - \frac{M_2 - M^*}{M_2 - M_1}(z_2 - z_1), \tag{3}$$

gives the height in meters of the duct bottom, where M_2 and z_2 are the M value and height at the duct middle, M_1 and z_1 are the M value and height at the previous level of the sounding (from the surface), and M* is the M value at the duct top, which is also equal to the M value at the duct bottom in the case of an elevated duct.

B. DESCRIPTION OF MATLAB ROUTINES USED IN PROCESSING OF SOUNDING DATA

Almost 1.7 million soundings contained in raw text files were read in, processed, and used for refractivity calculations. Almost 6000 lines of MATLAB routines were written for this study to process this data (Appendix). The following is a brief synopsis of the MATLAB routines written for this study to process the data:

- Read in all data files. Determine which soundings to use based on various quality control criteria. To ensure there is sufficient vertical resolution, each sounding must have all four necessary values at intervals no greater than 100 mb. Calculate M profiles from sounding data to determine duct information. Record surface temperature and dew point depression values.
- Determine if a duct exists in a given sounding (that is, determine if sounding has a segment with a negative dM/dz). If so, find duct height and thickness information of lowest three ducts of the sounding. Record critical values of T, e, P, Z, and M at the duct top and duct middle when present.
- By *season*, calculate statistics such as mean duct heights, duct thicknesses, and mean frequency of occurrence, as well as mean surface temperature and mean dew point depression. Calculate mean values of T, e, P, Z, and M at the duct top and duct middle when present.
- By *geographic region* and by season, determine statistics such as mean duct heights, duct thicknesses, and mean frequency of occurrence, as well as mean surface temperature and dew point depression. This information is then displayed in geographical form in a polar stereographic projection.

Based on the quality control criteria established for this study, only approximately 300,000 soundings were used of the almost 1.7 million available (Table 1 and Table 2). Among the various criteria used to discard a sounding were constraints on the vertical

resolution of the sounding, checks for missing data at a given vertical level, and checks for abnormal data values.

	Used	Discarded
HARA 1948-1950	10871	1859
HARA 1951-1960	102912	61351
HARA 1961-1970	105107	168407
HARA 1971-1980	52954	386906
HARA 1981-1990	16755	466397
HARA 1991-1996	0	176752
PTARMIGAN 1950-1961	0	10340
DOAR 1954-1990	1144	24667
NCDC 1998-2006	18269	143661
Total	308012	1440340

Table 1. Sounding data used.

Spring Total	73994
Summer Total	79279
Fall Total	79062
Winter Total	75677
Total Used	308012

Table 2. Soundings used broken down by season.

Unfortunately, not one sounding could be used from the HARA data set from 1991-1996 time periods, nor from the Ptarmigan data set. The main criteria that these soundings did not adhere to was having recorded values of pressure, height above surface, temperature, and dew point, where each recorded level was no more than 100mb apart.

III. CLIMATOLOGICAL ASPECTS OF DATA ANALYSIS

A. GEOGRAPHIC LOCATIONS OF SOUNDINGS

The main purpose of this chapter is to determine if the soundings used for the ducting statistics are representative of climatological conditions in the Arctic. This is done by comparing the lowest level of the sounding data with established climatologies, the latter based on many more data points than the sounding data. The data does not have ideal geographic coverage of the arctic, and many of these locations had a small number of total soundings (Figure 2). The number of soundings taken near the pole is significantly less than the land-based reporting stations. For a large number of the points shown below, only surface values could be retrieved.

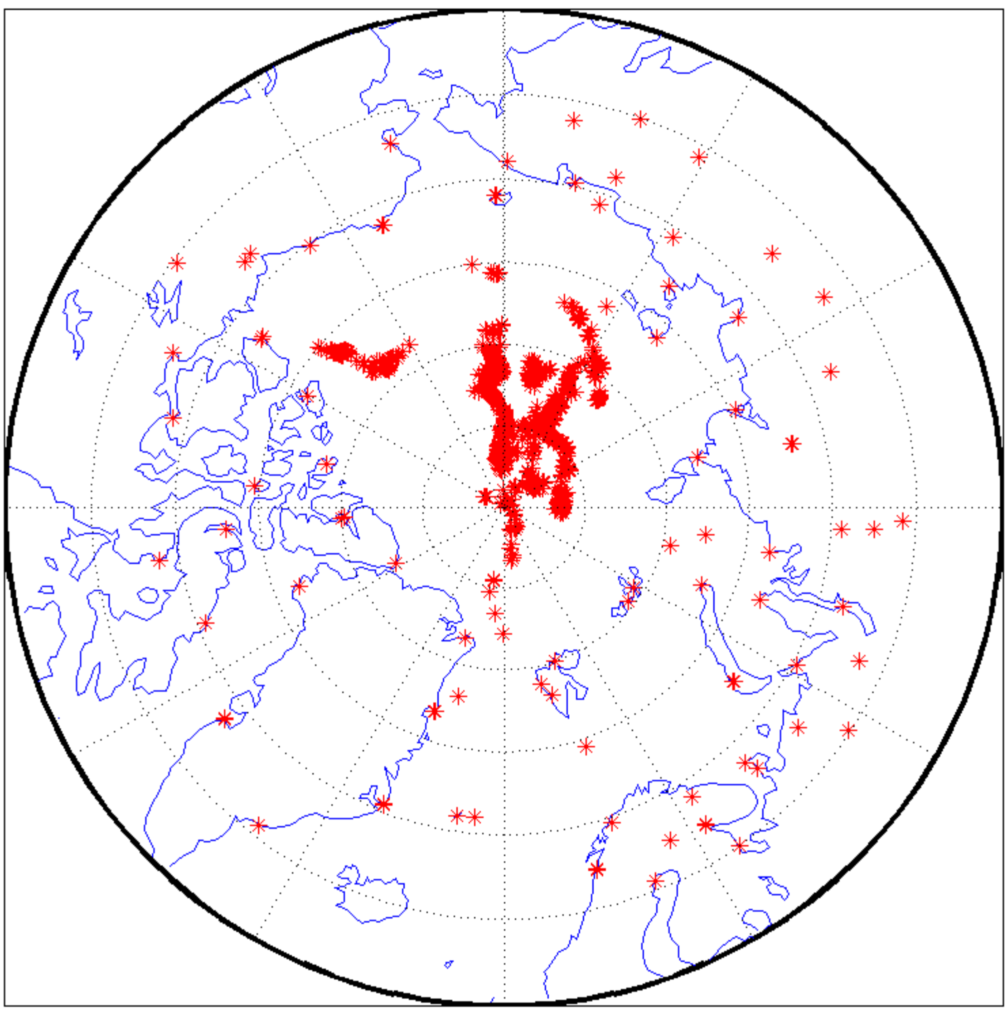

Figure 2. Locations of soundings used.

B. SEASONAL FEATURES OF TEMPERATURE AND DEW POINT DEPRESSION

The data were categorized by the following seasons: Spring, March – May; Summer, June – August; Fall, September – November; Winter, December – February. The mean surface temperatures for each season for the entire study region (Table 3) are reasonably in line with other studies for mean seasonal arctic temperatures for the same seasonal convention (Rigor, et. al, 1997).

	Season			
	Spring	**Summer**	**Fall**	**Winter**
$\overline{T}_{SFC}$ (C)	**-16.5**	**4.5**	**-10.7**	**-25.8**
$\overline{(T - T_d)}_{SFC}$ (C)	**4.5**	**3.4**	**3.3**	**4.7**

Table 3. Mean surface temperature and mean surface dew point depression by season.

C. SURFACE TEMPERATURES OF SOUNDING LOCATIONS

For the soundings that met the quality criteria, the surface temperature was recorded and then averaged for the all the soundings near that same location. The resulting mean temperature was then color shaded to show a geographic representation for the sounding locations north of 65 degrees north latitude, by respective season (Figures 3 through 6; white space denotes that no data were recorded for that area). These results compared relatively well with surface temperature climatology data for the same months via the GEMPAK Analysis and Rendering Program (GARP) for 1979-1998 (Appendix).

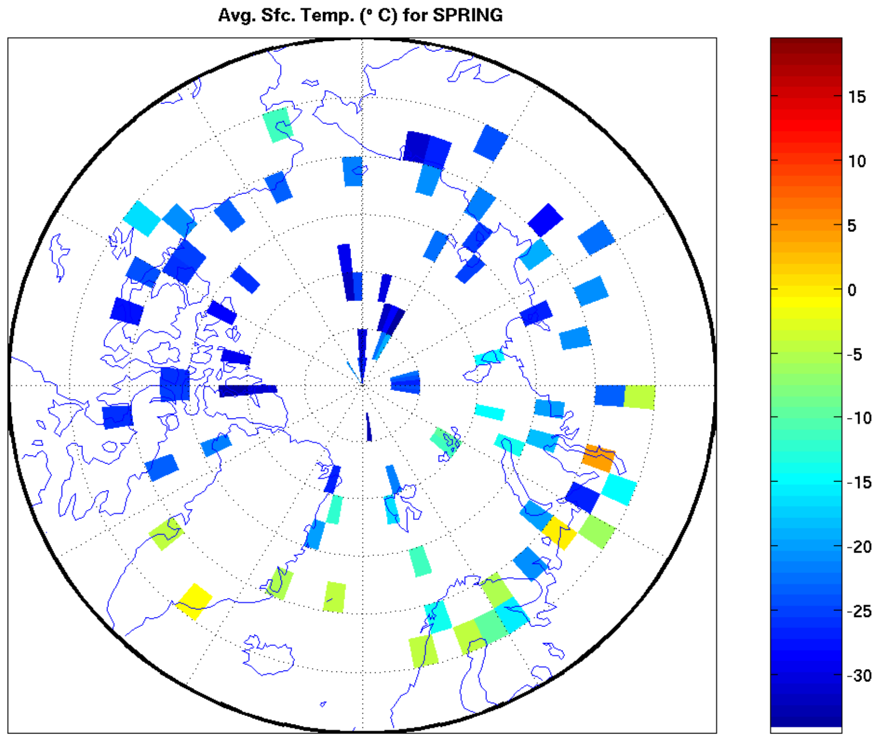

Figure 3. **Spring** average surface temperatures near each sounding location.

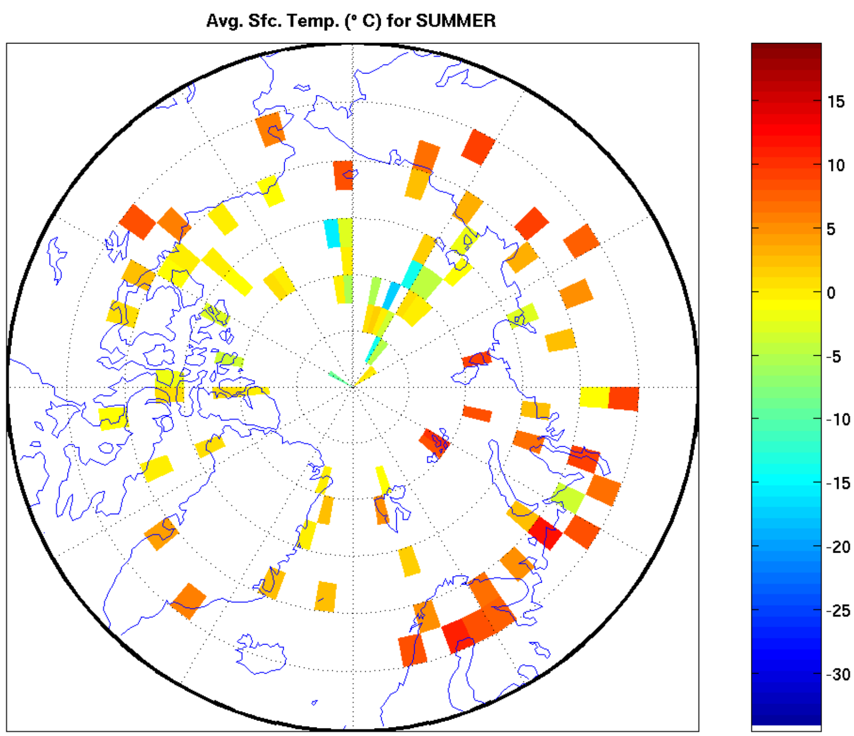

Figure 4. **Summer** average surface temperatures for each sounding location.

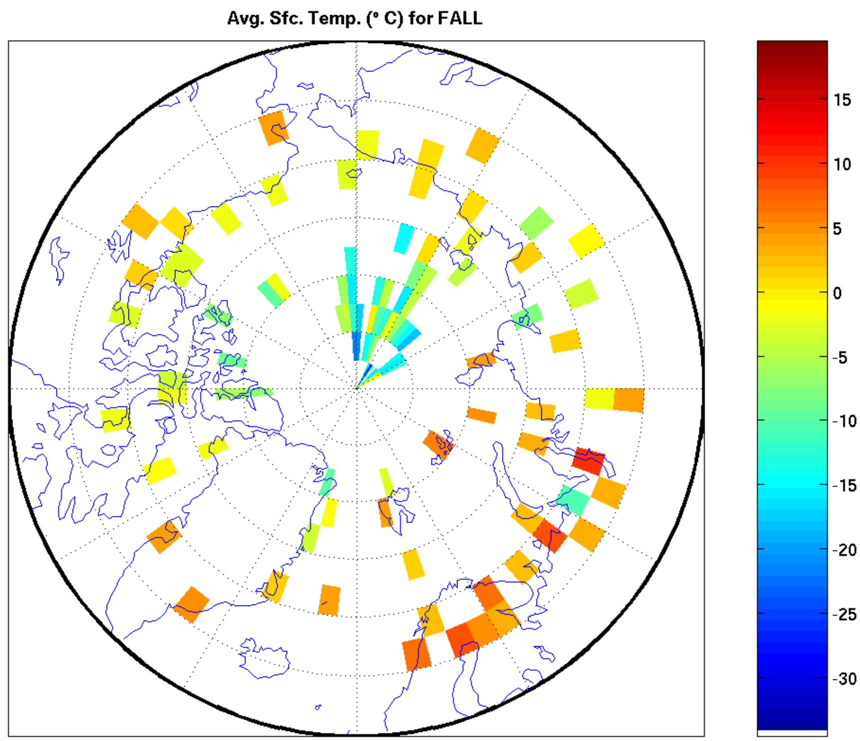

Figure 5. **Fall** average surface temperatures for each sounding location.

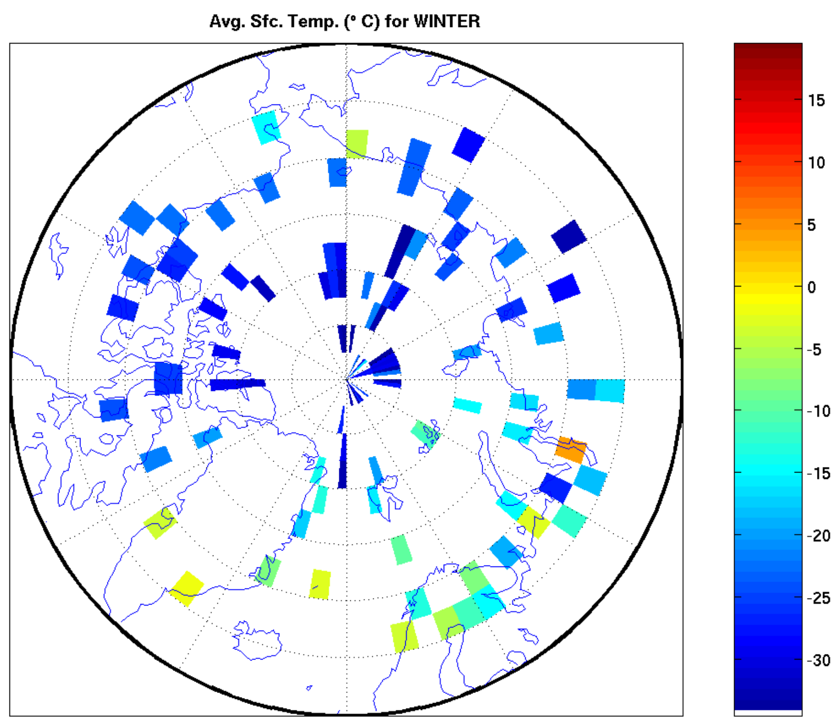

Figure 6. **Winter** average surface temperatures for each sounding location.

D. DEWPOINT DEPRESSION OF SOUNDING LOCATIONS

For the soundings that met the quality criteria, the surface dew point depression was recorded and then averaged for the all the soundings at that same location for the sounding locations north of 65 degrees north latitude for each respective season (Figures 7 through 10; white space denotes that no data were recorded for that area). These results compared relatively well with the areas of relative dryness or humidity for the same months, compared to climatology data from GARP for 1979-1998 (Appendix).

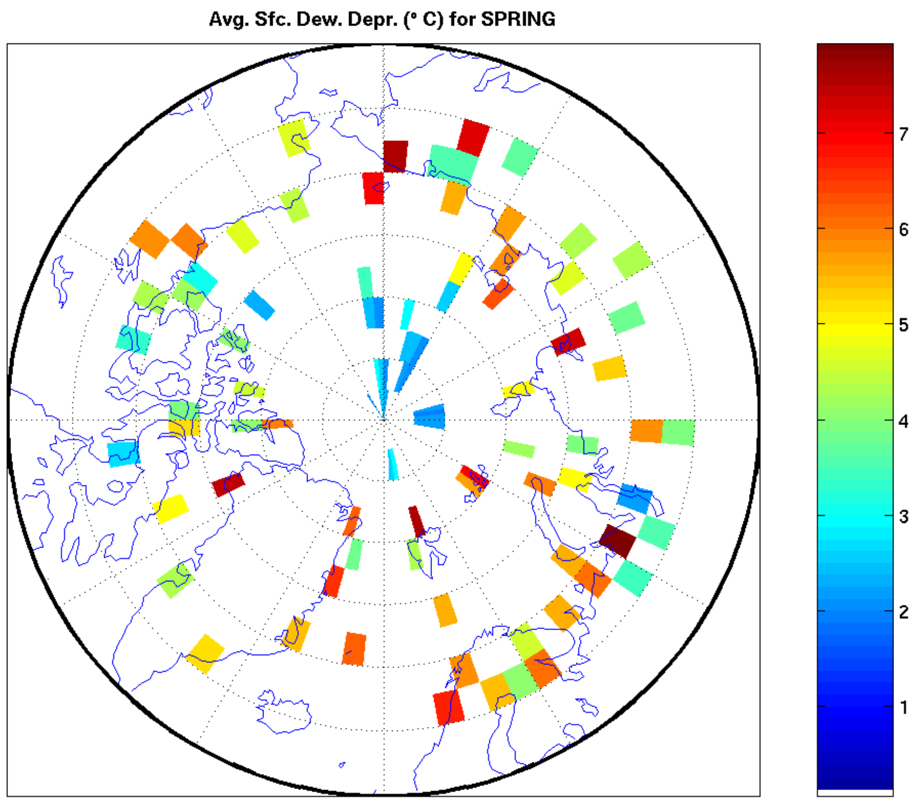

Figure 7. **Spring** average dew point depression for each sounding location.

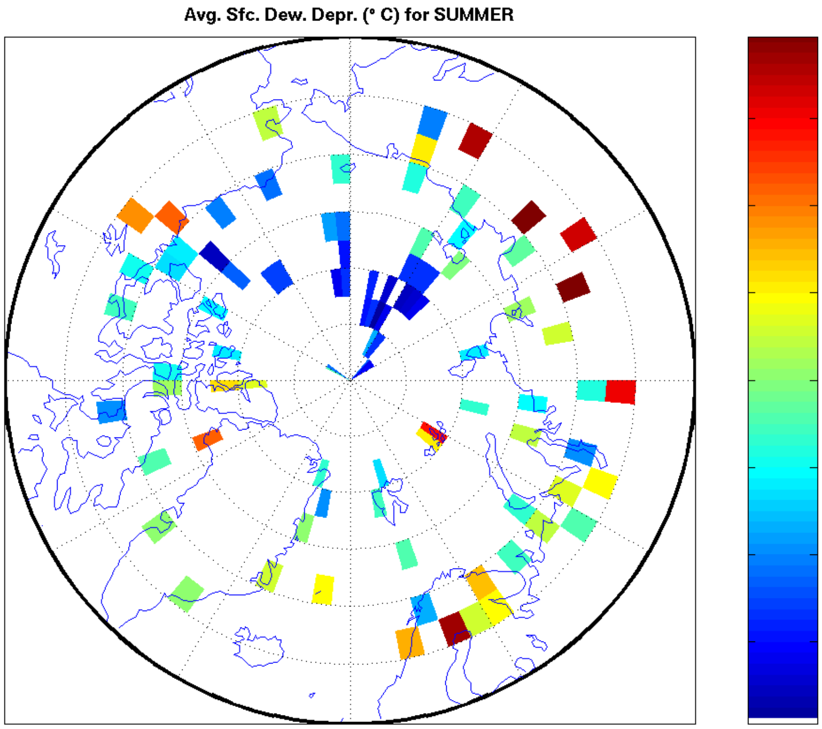

Figure 8. **Summer** average dew point depression for each sounding location.

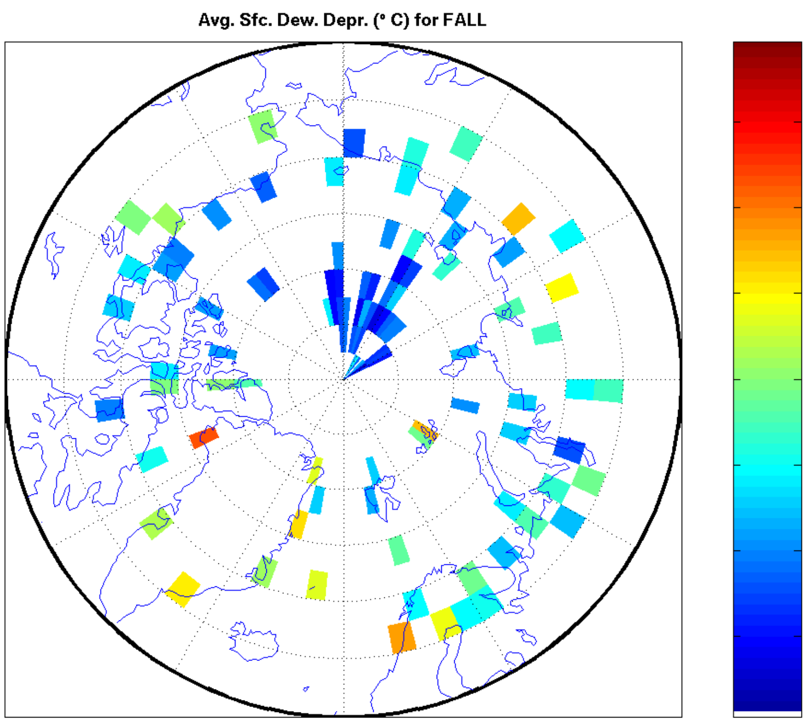

Figure 9. **Fall** average surface dew point depressions for each sounding location.

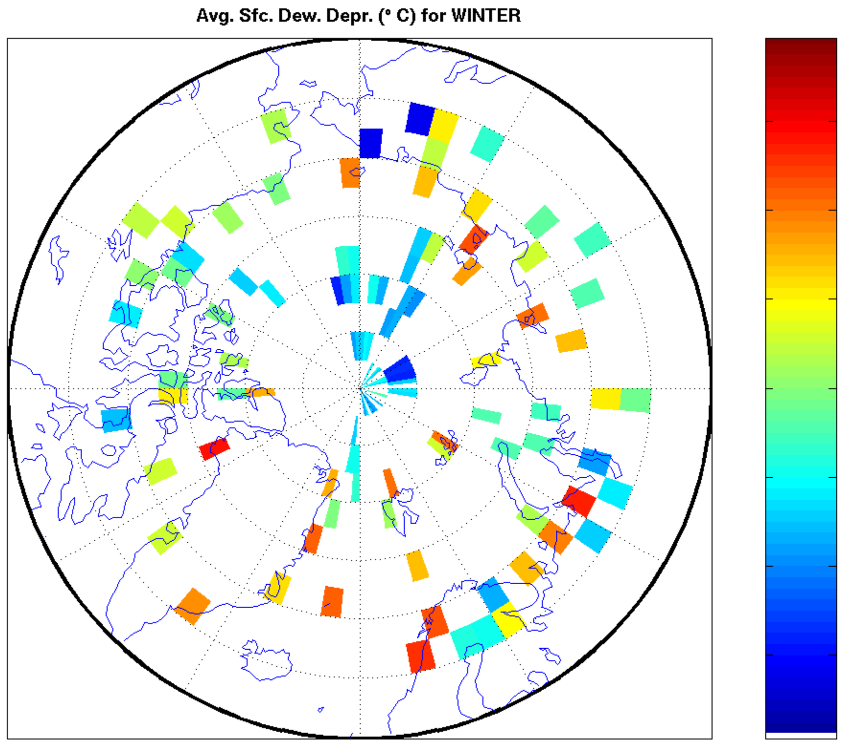

Figure 10. **Winter** average surface dew point depressions for each sounding location.

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IV. RESULTS

A. FREQUENCY OF OCCURRENCE OF DUCTS

Of the usable soundings, the percentage occurrence that at least one duct was found in the vertical M profile, by season, was calculated (Table 4). While the summer months showed a frequency of ducting occurrence of almost five percent, the other three seasons showed a frequency of ducting occurrence of only two to three percent. Occurrence of multiple ducting layers was rare.

	Season			
	Spring	Summer	Fall	Winter
At least one duct (%)	2.1	4.6	2.0	2.7
Only one duct (%)	2.1	4.1	1.9	2.7
Two ducts (%)	< 0.1	0.4	< 0.1	< 0.1
Three ducts (%)	< 0.1	< 0.1	< 0.1	< 0.1

Table 4. Percent occurrence of ducts found in the soundings, by season.

B. DUCT FEATURES BY SEASON

The three nearest-surface ducts, when present, were examined by season. Average duct heights for the lowest duct were highest for the summer months and lowest for winter months (Table 5). The second and third lowest ducts showed similar patterns, except for the third duct in fall months, which may be a result of the low total number of sounding examples with three ducts in winter months. Duct thicknesses were greater in summer months, and less in winter months (Table 6). Higher duct heights and greater thicknesses in summer months were likely due to higher occurrences of surface heating and advection of warmer temperatures associated with the summer season.

	First (Nearest-Surface) Duct			
	SPRING	SUMMER	FALL	WINTER
Mean Height (m)	442	686	586	238
Std. Dev. (m)	669	896	777	468
Lower Quartile (m)	58	68	62	31
Median (m)	140	301	181	66
Upper Quartile (m)	580	915	910	202
	Second Duct			
	SPRING	SUMMER	FALL	WINTER
Mean Height (m)	1399	1756	1757	790
Std. Dev. (m)	1120	1034	1133	750
Lower Quartile (m)	481	862	951	281
Median (m)	1075	1639	1661	546
Upper Quartile (m)	2112	2494	2394	890
	Third Duct			
	SPRING	SUMMER	FALL	WINTER
Mean Height (m)	1436	2118	2468	1865
Std. Dev. (m)	198	956	1300	420
Lower Quartile (m)	1301	1371	1470	1617
Median (m)	1394	2261	2608	1636
Upper Quartile (m)	1571	2739	3466	2172

Table 5. Duct height statistics for the three nearest-surface ducts, when present.

	First Duct			
	SPRING	SUMMER	FALL	WINTER
Mean Thickness (m)	59	103	66	48
Std. Dev. (m)	47	76	67	36
Lower Quartile (m)	23	48	22	22
Median (m)	50	95	54	42
Upper Quartile (m)	84	141	96	69
	Second Duct			
	SPRING	SUMMER	FALL	WINTER
Mean Thickness (m)	78	102	79	61
Std. Dev. (m)	68	58	47	46
Lower Quartile (m)	47	65	45	24
Median (m)	67	91	77	52
Upper Quartile (m)	97	125	107	87
	Third Duct			
	SPRING	SUMMER	FALL	WINTER
Mean Thickness (m)	62	103	83	74
Std. Dev. (m)	37	115	30	12
Lower Quartile (m)	31	55	65	67
Median (m)	64	85	95	67
Upper Quartile (m)	94	109	102	82

Table 6. Duct thickness statistics for the three nearest-surface ducts, when present.

When a duct was present, the summer months had the highest percentage occurrence of the nearest-surface duct to be elevated compared to other months. The winter months displayed the highest percentage occurrence of surface-based ducts (Figure 11). The higher percentage of elevated ducts in summer months is likely a mechanism of increased frequency of surface heating and advection processes more common in this season. The higher percentage of surface-based ducts in winter months is likely a mechanism of radiational cooling of the surface and the low availability of moisture at the surface.

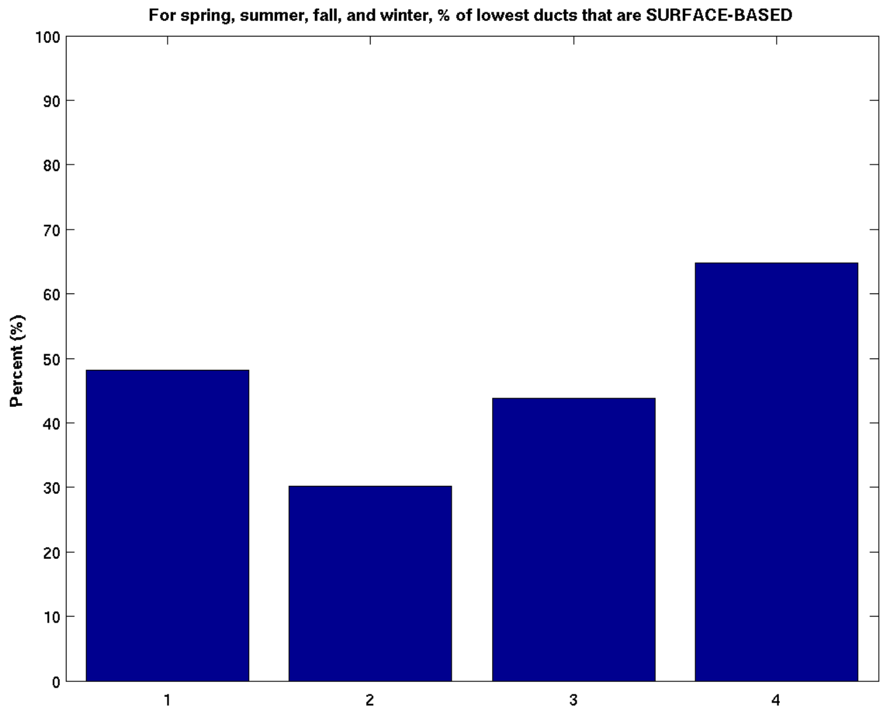

Figure 11. Percent of soundings with ducts that were surface-based (from left to right: spring, summer, fall, and winter).

C. SURFACE TEMPERATURE AND VAPOR PRESSURE DIFFERENCES

For average surface values of temperature and vapor pressure were compared when ducting conditions are present to when they are not present. For spring, summer, and fall months, surface temperatures are slightly warmer when a duct is present. For winter months, surface temperatures are slightly cooler when a duct is present (Table 7). For spring, summer, and fall months, surface vapor pressures are slightly higher when a duct is present. For winter months, surface vapor pressures are slightly lower when a duct is present (Table 8). These results are consistent with the previously mentioned mechanisms of advection and surface heating for the warmer months of spring, summer, and fall, along with the mechanism of raditional cooling for winter months. As the standard errors of the surface temperatures and surface vapor pressures are less than the differences of the means of these values, the differences are random variations alone and are therefore again point to the aforementioned seasonal mechanisms.

	SPRING	SUMMER	FALL	WINTER
$\overline{T}_{SFC}$, duct present (C)	-15.91	4.8	-8.16	-28.03
Std. Error, duct present	0.34	0.09	0.32	0.22
$\overline{T}_{SFC}$, no duct present (C)	-16.55	4.43	-10.7	-25.73
Std. Error, no duct present	0.04	0.02	0.04	0.04
Difference in means	0.65	0.36	2.54	-2.3
Root of squared errors	0.34	0.09	0.33	0.22

Table 7. Surface temperature differences when a duct is present and when a duct is not present

	SPRING	SUMMER	FALL	WINTER
$\overline{e}_{SFC}$, duct present (mb)	2.27	7.37	3.8	0.69
Std. Error, duct present	0.06	0.04	0.07	0.03
$\overline{e}_{SFC}$, no duct present (mb)	1.81	6.92	2.93	0.77
Std. Error, no duct present	0.01	0.01	0.01	0.00
Difference in means	0.46	0.45	0.87	-0.08
Root of squared errors	0.06	0.04	0.07	0.03

Table 8. Surface vapor pressure differences when a duct is present and when a duct is not present.

D. DUCT OCCURRENCE OVER GEOGRAPHY

For each sounding location, the number of times a duct was found in a sounding was divided by the total number of soundings available for that location, to determine a percent occurrence of when a duct was present. These percentage results were then color coded and displayed in their respective seasons. During the spring months (Figure 12), most areas showed low percentages of duct occurrence, with a few areas of higher occurrence such as near the Scandinavian countries. During the summer months (Figure 13), there are many areas of low percentage of ducting occurrence; however, there are many areas of increased ducting frequency, compared to spring months, with some areas reaching up to 20% frequency of occurrence. For fall months (Figure 14), the areas of high occurrence are generally in the same locations as the areas of high occurrence for summer months. For spring, summer, and fall months, the areas of higher occurrence of ducts near Alaska and Scandinavia seem to coincide with areas where climatology shows a mean state of warm air advection (Appendix). For winter months (Figure 15), the areas of higher occurrence of ducts shift somewhat. This is likely due to the different contributing mechanism of radiation cooling more common to winter months vice advection or surface heating.

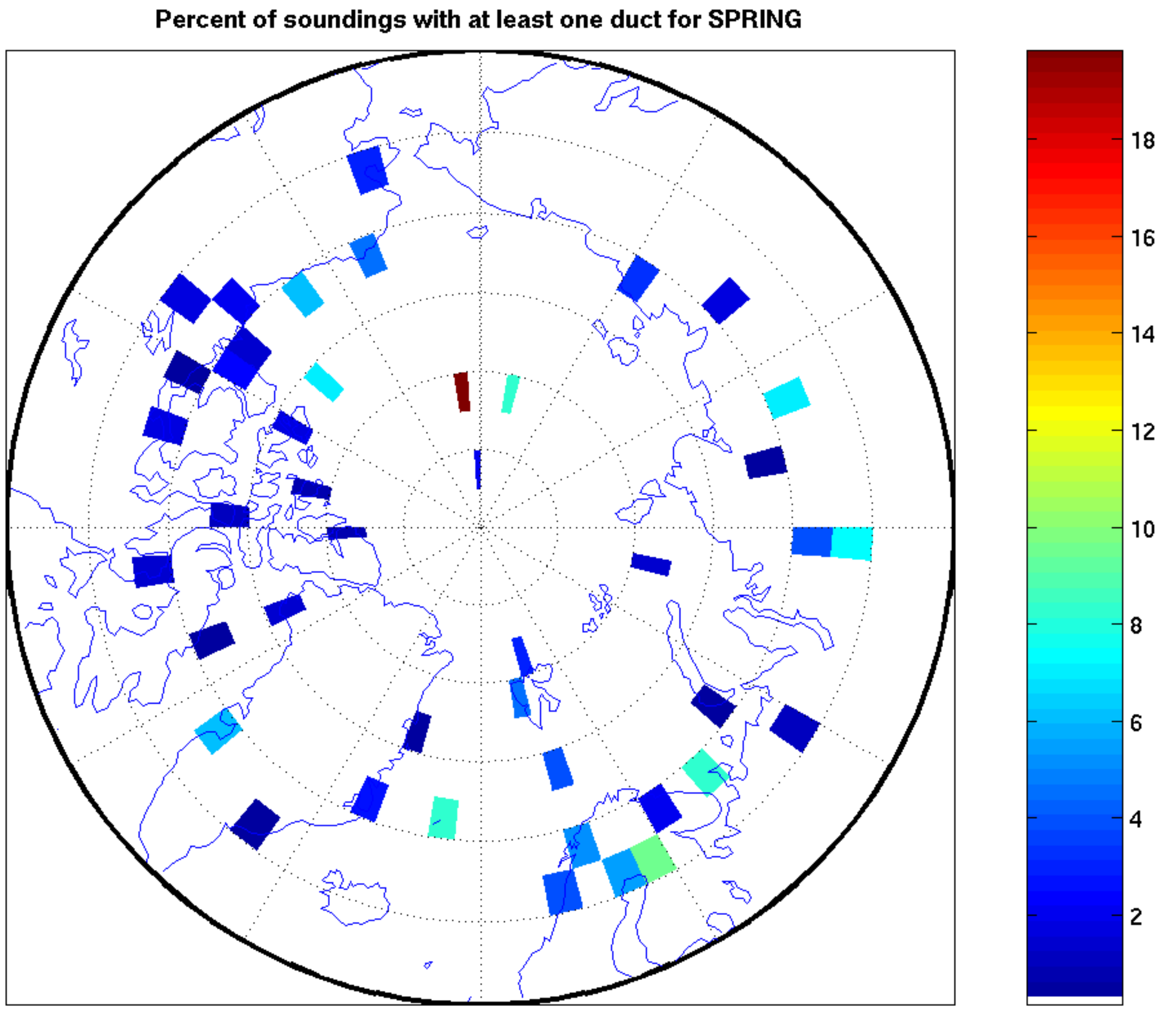

Figure 12. Percent occurrence at a sounding location where at least one duct existed in the vertical, for **spring** months.

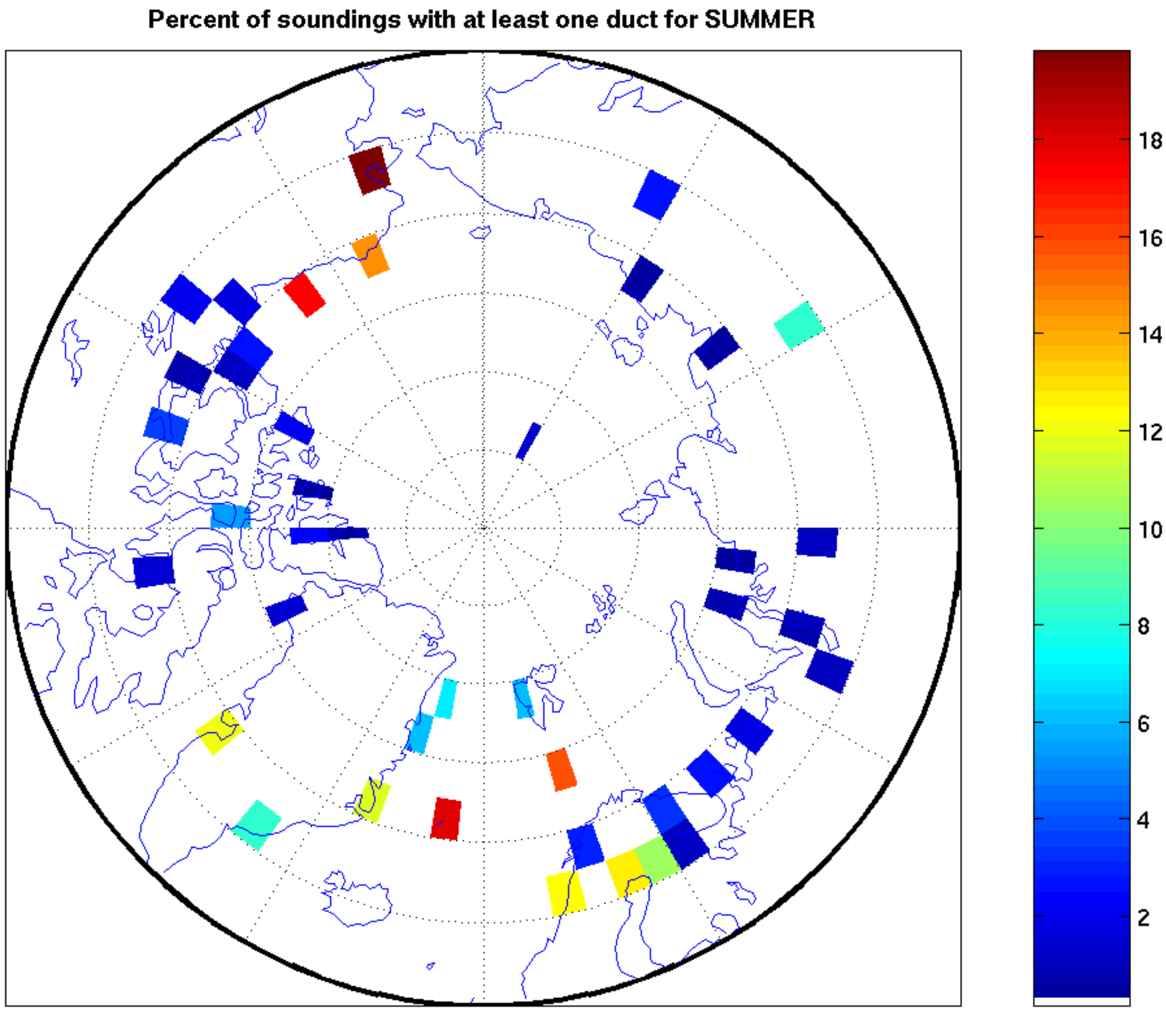

Figure 13. Percent occurrence at a sounding location where at least one duct existed in the vertical, for **summer** months.

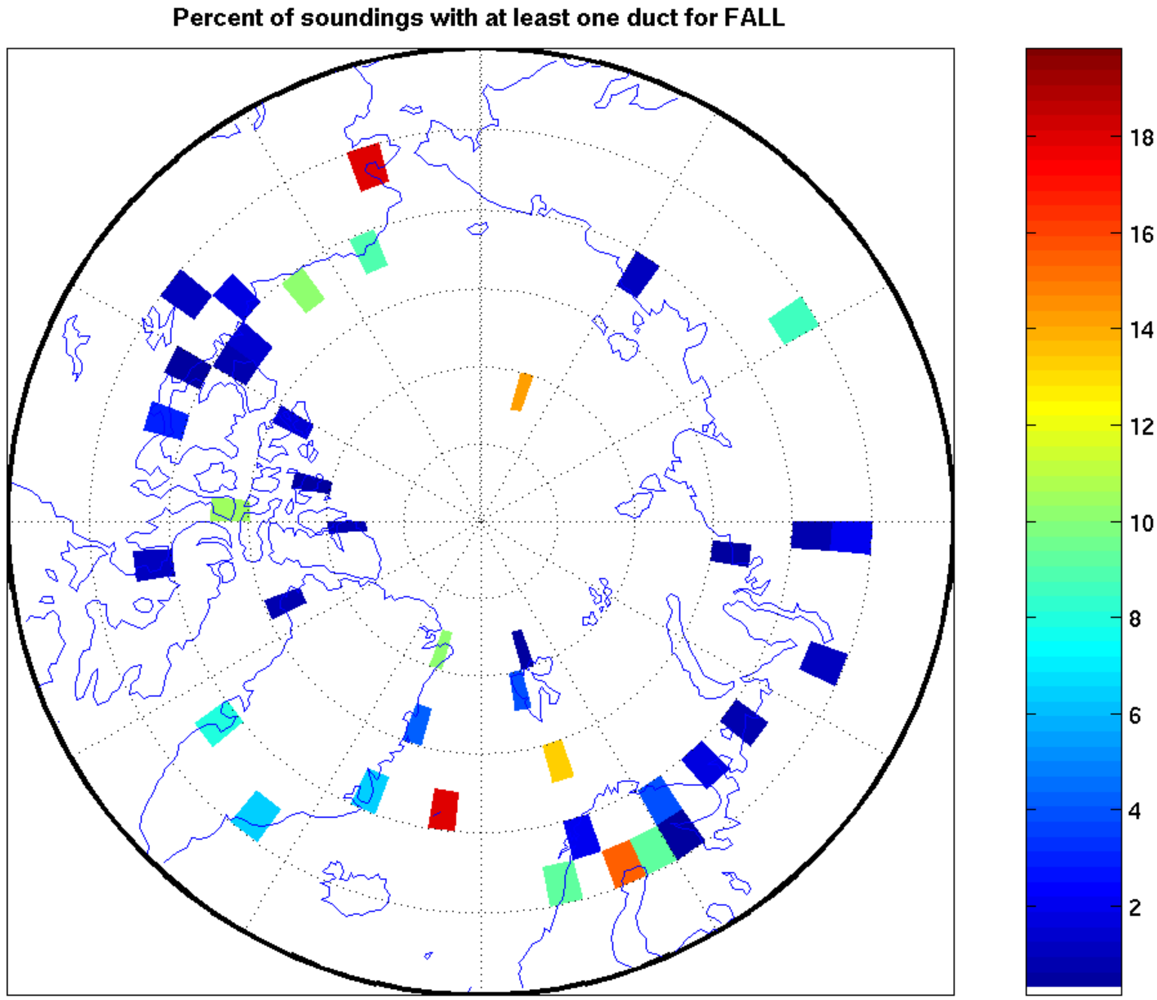

Figure 14. Percent occurrence at a sounding location where at least one duct existed in the vertical, for **fall** months.

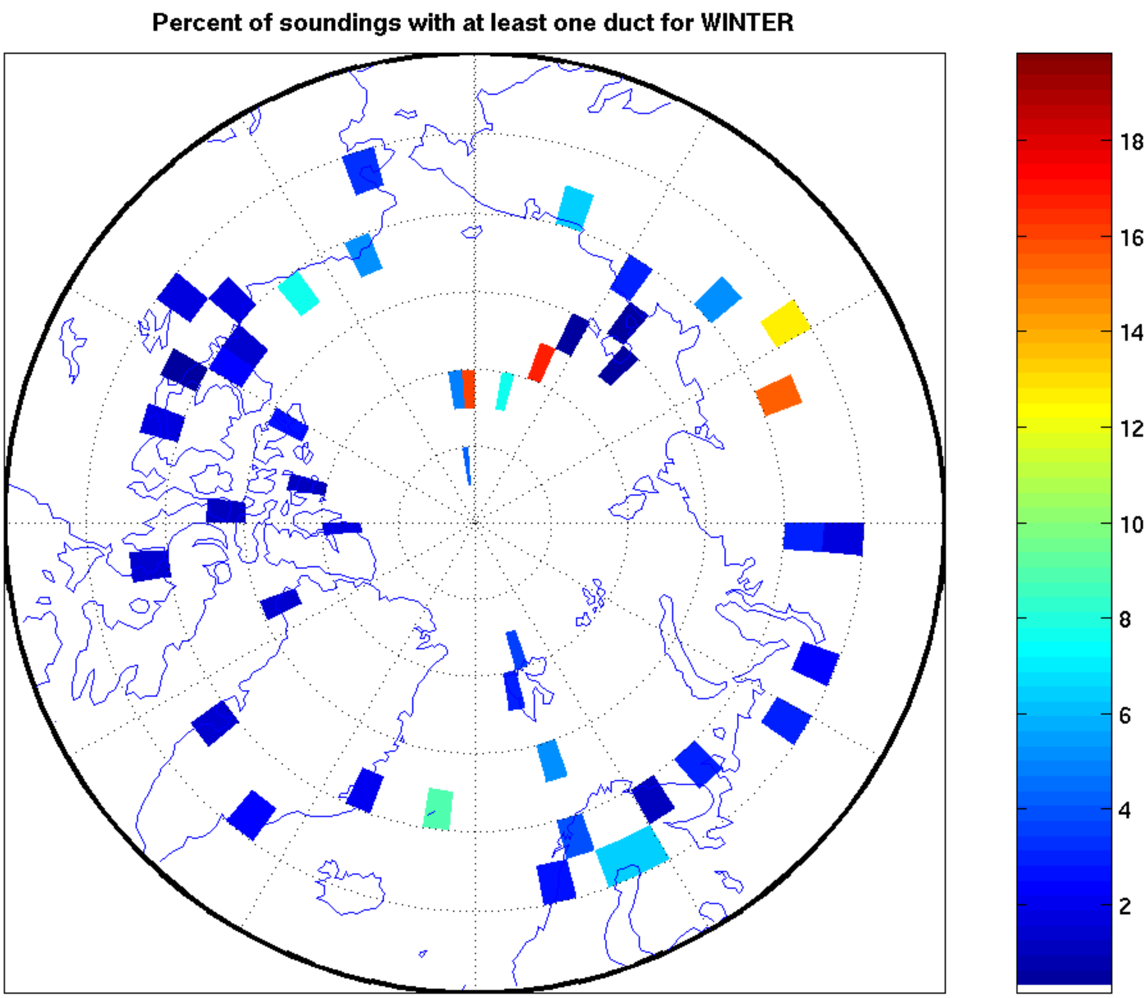

Figure 15. Percent occurrence at a sounding location where at least one duct existed in the vertical, for **winter** months.

E. DUCT CHARACTERISTICS

For all the nearest-surface ducts that were present, values of $\overline{T}$, $\overline{P}$, $\overline{Z}$, and $\overline{e}$ at the duct top and at the optimal coupling height (duct middle) were averaged (Table 9).

	Spring		Summer		Fall		Winter	
	Top	Middle	Top	Middle	Top	Middle	Top	Middle
$\overline{T}$ (C)	-12.59	-15.74	5.52	4.39	-7.47	-9.53	-22.17	-27.06
$\overline{e}$ (mb)	1.13	1.3	3.93	6.65	1.69	2.34	0.6	0.44
$\overline{P}$ (mb)	958.97	965.92	928.77	937.31	939.88	946.59	982.15	989.08
$\overline{Z}$ (m)	487.35	442.37	755.41	685.5	632.48	585.95	278.7	237.91

Table 9. Mean values of $\overline{T}$, $\overline{P}$, $\overline{Z}$, and $\overline{e}$ at duct top and duct middle, by season.

These average values were then subtracted to give the delta of the average of that particular value (Table 10). The least difference in temperature over the trapping layer ($\Delta\overline{T}$) is in the summer and the greatest in the winter. The least difference in vapor pressure ($\Delta\overline{e}$) occurs in the winter months, and the greatest difference in the summer months. The greatest trapping layer thicknesses ($\Delta\overline{Z}$) occur in the summer months, and the least in the winter months. The most negative vertical M gradient ($\Delta\overline{M} / \Delta\overline{Z}$) occurs in summer months, while the least negative vertical M gradient occurs in the winter months.

	Season			
	Spring	Summer	Fall	Winter
$\Delta\overline{T}$ (C)	3.15	1.13	2.06	4.89
$\Delta\overline{e}$ (mb)	-0.16	-2.73	-0.65	0.15
$\Delta\overline{P}$ (mb)	-6.95	-8.54	-6.71	-6.94
$\Delta\overline{Z}$ (m)	44.98	69.91	46.53	40.79
$\Delta\overline{M}$	-2.31	-5.04	-2.62	-1.78
$\Delta\overline{M} / \Delta\overline{Z}$	-0.05	-0.07	-0.06	-0.04

Table 10. Delta values from top of duct to optimal coupling height, by season.

Based on Equation (2), the main contributors to the vertical profile of M are the vertical profiles of temperature and vapor pressure. To estimate the relative contribution

of temperature and vapor pressure changes on duct formation, the effect of each of these values using in Equation (2) were compared. The value $\widetilde{M}_{TOP}$ was calculated by using the average values of temperature and vapor pressure at the duct top and duct middle with Equation (2). The value $\widetilde{M}_{TOP}$ was then recalculated by holding either temperature and/or vapor pressure constant from the value at the duct middle. This was done to simulate the effect of having a layer of constant vapor pressure or constant temperature in the trapping layer so that the relative contribution of each parameter could be isolated. The ratios of the differences of these simulated $\widetilde{M}_{TOP}$ values and the baseline $\widetilde{M}_{TOP}$ values were then compared to determine what percentage contribution that either the vapor pressure gradient or the temperature gradient had to the trapping layer (Table 11). For these calculations, the temperature and humidity contributions were treated as linear effects.

For summer and fall months, contribution from the vapor pressure gradient dominated the duct feature, but there was some contribution from the temperature gradient for these seasons as well. For spring months, the contribution from the temperature gradient dominated the duct feature, with some contribution from the vapor pressure gradient. For winter months, the contribution from the temperature gradient dominated the duct feature, and the vapor pressure gradient actually had a negative contribution, meaning on average it worked against the formation of the trapping layer. These results for winter and spring are in contrast to most other locations globally, where humidity gradients are the most important contributors to duct formation (Davidson, 2002).

	Spring		Summer		Fall		Winter	
$\widetilde{M}_{TOP}$	368.33		396.13		382.76		350.98	
$\widetilde{M}_{TOP}$, constant e	371.98		397.34		385.05		357.16	
$\widetilde{M}_{TOP}$, constant T	369.27		409.21		386.20		350.03	
$\widetilde{M}_{TOP}$, both constant	372.94		410.52		388.54		356.17	
% Contribution to $\Delta\widetilde{M}$ from e-effect and T-effect	20.20%	78.80%	90.20%	8.33%	58.96%	39.18%	-18.42%	119.90%

Table 11. Comparison of effects to $\Delta\widetilde{M}$ from holding either e or T constant, by season. This simulates the effect of having a layer of constant vapor pressure or constant temperature in the trapping layer to determine their individual linear contributions to the trapping layer.

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V. SUMMARY

A. LIMITATIONS

The number of soundings with recorded values of P, Z, T, and T_d at no greater than 100 mb between sounding levels available for this study was only roughly one fifth of the total soundings from all the data sets. Even so, these higher quality soundings did not have sufficient vertical resolution to show evaporative-type ducting features. Also due to the lack of preferred higher vertical resolution, these results probably represent a low estimate to the percentage occurrence of ducts in these regions. Additionally, these soundings did not cover an ideal geographic spacing over the Arctic region, especially for contour-style plotting of results or to establish well-defined causes or patterns in the ducting features spatially.

B. CONCLUSIONS

For the entire Arctic region, the summer months showed a frequency of ducting occurrence of roughly five percent, while the other three seasons showed a frequency of ducting occurrence of only two to three percent. However, some individual local areas reach up to 20% frequency of occurrence. When a duct is present, the mean duct heights are higher for the summer months. Mean duct thicknesses are greater in summer months. On average, the highest occurrence of elevated ducts is in the summer months, and the highest occurrence of surface-based ducts is in the winter months. Mean surface temperatures are slightly warmer when a duct is present for spring, summer, and fall months and slightly cooler for winter months. Mean surface vapor pressure is slightly greater when a duct is present for spring, summer, and fall months, and slightly less for winter months. Mean duct heights are greater in summer and fall seasons. Mean duct thicknesses are greater in the summer months. The least difference in mean temperature over a duct is in the summer and the greatest in the winter. The least difference in mean vapor pressure occurs in the winter months, and the greatest difference in the summer months. The most negative average vertical M gradient occurs in summer months, while the least negative average vertical M gradient occurs in the winter months.

For summer and fall months, the vapor pressure gradient contributed more to the formation of the duct feature, but there was some contribution from the temperature

gradient for these seasons as well. For spring months, the temperature gradient contributed more to the formation of the duct feature, with some contribution from the vapor pressure gradient. For winter months, the contribution from the temperature gradient dominated the duct feature, and the vapor pressure gradient actually had a negative contribution, meaning on average it worked against the formation of the duct feature.

APPENDIX

Webpage links to MATLAB routines used in this thesis:

www.met.nps.navy.mil/~guestps/stahlhut/cycledir.m

www.met.nps.navy.mil/~guestps/stahlhut/bargraphs.m

www.met.nps.navy.mil/~guestps/stahlhut/DAORcycle.m

www.met.nps.navy.mil/~guestps/stahlhut/fine_inv_color_map.m

www.met.nps.navy.mil/~guestps/stahlhut/NOAAcycle.m

www.met.nps.navy.mil/~guestps/stahlhut/ptarmigancycle.m

www.met.nps.navy.mil/~guestps/stahlhut/locationplotter.m

www.met.nps.navy.mil/~guestps/stahlhut/fineboxdata.m

www.met.nps.navy.mil/~guestps/stahlhut/numbers.m

Webpage links to additional figures:

Seasonal Mean Temperature, Humidity, and MSLP for 1979-1998 from GARP:

www.met.nps.navy.mil/~guestps/stahlhut/seasonalGARP.html

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   Monterey, California

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   United States Naval Observatory
   Washington, DC

4. Dr. Jonathan D. W. Kahl
   Dept. Of Geosciences
   University of Wisconsin-Milwaukee
   Milwaukee, Wisconsin

5. National Snow and Ice Data Center
   NCDIC User Services
   Boulder, Colorado

6. National Ice Center
   National Ice Center Liaison
   Washington, DC